# Estimation of Total Above-Ground Phytomass Production Using Remotely Sensed Data*

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Remote sensing potentially offers a quick and nondestructive method for monitoring plant canopy condition and development. In this study, multispectral reflectance and thermal emittance data were used in conjunction with micrometeorological data in a simple model to estimate above-ground total dry phytomass production of several spring wheat canopies. The fraction of absorbed photosynthetic radiation (PAR) by plants was estimated from measurements of visible and near-infrared canopy reflectance. Canopy radiation temperature was used as a crop stress indicator in the model. Estimated above-ground phytomass values based on this model were strongly correlated with the measured phytomass values for a wide range of climate and plant-canopy conditions.

## Introduction

In recent years, agricultural remote sensing has been mainly concerned with developing fundamental relationships for assessing plant condition and development based on the emitted and reflected radiation from the plant canopy.

Emitted thermal radiation from plant canopies has been related to evapotranspiration and plant water status (Monteith and Szeicz, 1962; Idso et al., 1977, Jackson et al., 1977). Photosynthetically active radiation (PAR) absorbed by plants and green leaf area has been estimated with measurements of reflected visible and near infrared radiation from the plant canopy (Asrar et al., 1984b, c; Hatfield et al., 1984a, b).

The feasibility of utilizing multispectral reflectance data for estimating dry phytomass production was addressed by Aase and Siddoway (1981), who developed regression equations between canopy spectral reflectance and total dry phytomass of wheat. Their results were linear from tillering until flowering but departed from linearity at the onset of senescence. Tucker et al. (1981) found that the ratio of near-infrared to red reflectance and the normalized difference vegetation index were strongly related to above-ground total phytomass in winter wheat. Park and Deering (1982) used a modified Kubelka–Munk radiative transfer model to describe variations of the diffuse spectral reflectance due to changes in standing total dry phytomass.

The limitations of empirically derived relations for assessing dry phytomass pro-

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duction from spectral reflectance data are due, in part, to the fact that physical and physiological processes are not taken into account.

Our objective was to develop a method, based on physical and physiological principles, by which emitted thermal infrared and reflected visible and near-infrared radiation can be used to estimate above-ground total dry phytomass production over a season.

## Theoretical Considerations

Monteith (1972) showed that the relation between the production of total dry phytomass and the photosynthetically active portion of solar radiation (PAR) absorbed by plants could be written as

$$M = \sum_{i=1}^{n} \varepsilon_c \varepsilon_i \varepsilon_s SC, \qquad (1)$$

where $M$ is total dry phytomass, $n$ is a time index (i.e., number of days), $\varepsilon_c$ is the photochemical efficiency factor, $\varepsilon_i$ is the fraction of absorbed PAR, $\varepsilon_s$ is the fraction of energy in the PAR region of the electromagnetic spectrum, S is the total incident solar radiation ($\mathrm{J\,m^{-2}d^{-1}}$), and $C$ is a crop stress index.

The photochemical factor $\varepsilon_c$ is the ratio of chemical energy produced as dry phytomass to absorbed PAR energy. Earlier studies (Monteith, 1972; 1977) indicated that $\varepsilon_c$ was relatively constant for a given crop. Asrar et al. (1984a) found that $\varepsilon_c$ values, based on above-ground total phytomass for winter wheat, were affected by management practices and stages of physiological development. Analysis of theoretical calculations and experimental measurements by Szeicz (1974) showed that the PAR fraction of the solar spectrum, $\varepsilon_s$, was nearly constant for the total (direct + diffuse) radiation and nearly independent of atmospheric conditions. Hipps et al. (1983) evaluated the diurnal and seasonal variation of $\varepsilon_i$ using measurements of PAR components in winter wheat canopies. Asrar et al. (1984b) established a procedure by which $\varepsilon_i$ can be estimated from measurements of red and near-infrared spectral reflectance of plant canopies.

The crop stress index $C$ should include the effects of water as well as temperature stress (Daughtry et al., 1983). Water stress and plant canopy temperature, however, can be related. Therefore, $C$ can be related to the ratio of actual $E$ to potential $E^*$ evapotranspiration by an energy balance approach (Jackson, 1982) as

$$C = \frac{E}{E^*} = \frac{\Delta + \gamma^*}{\Delta + \gamma(1 + r_c/r_a)}, \qquad (2)$$

where $\gamma^*$ is defined as

$$\gamma^* = \gamma(1 + r_c^*/r_a) \qquad (3)$$

and $\Delta = (e_c^* - e_a^*)/(T_c - T_a)$ is the slope of saturation vapor pressures $e_c^*$ and $e_a^*$ at canopy $T_c$ and air $T_a$ temperatures, respectively, $\gamma$ is the psychrometric constant, and $r_c^*$ is crop resistance to vapor transfer under potential (ample water) conditions. To evaluate $E/E^*$ from Eq. (2), a value for crop resistance to water vapor transport, $r_c$, and one for aerodynamic resistance, $r_a$, are required. Jackson (1982) derived the following $r_c/r_a$ relation based on the energy balance of a plant canopy:

$$\begin{aligned} r_c/r_a = \{ [\gamma r_a R_n/(\rho C_a)] - (T_c - T_a) \\ \times (\Delta + \gamma)(e_a^* - e_a) \} \\ / \gamma [(T_c - T_a) - r_a R_n/(\rho C_a)], \end{aligned} \qquad (4)$$

**TABLE 1** Planting, Emergence, Irrigation Dates (Day of Year) and Total Applied Water for the 1979–1980 Experiment on Produra Wheat at Phoenix, AZ

| Treatment | Planting Date | Emergence Date | Irrigation Dates | Irr. and Rain (mm) |
|---|---|---|---|---|
| A1 | 271 | 275 | 271, 278, 289, 334 | 517 |
| B1 | 271 | 275 | 271, 278, 290, 313, 345 | 676 |
| C1 | 271 | 275 | 272, 278, 290, 324 | 529 |
| A2 | 295 | 302 | 295, 302, 334 | 474 |
| B2 | 295 | 302 | 296, 302, 324 | 461 |
| C2 | 295 | 302 | 296, 302, 317, 345 | 527 |
| A3 | 318 | 330 | 319, 351 | 347 |
| B3 | 318 | 330 | 319, 079 | 357 |
| C3 | 318 | 330 | 320, 351 | 343 |
| A4 | 352 | 363 | 353 | 241 |
| B4 | 352 | 363 | 353, 079, 099 | 437 |
| C4 | 352 | 363 | 354, 098 | 364 |
| A5 | 036 | 047 | 039, 100 | 321 |
| B5 | 036 | 047 | 039, 079, 106, 123, 134 | 598 |
| C5 | 036 | 047 | 039, 093, 114 | 410 |

where $R_n$ is the net radiation, $\rho$ and $C_a$ are density and heat capacity of the air, and $e_a$ is the actual air vapor pressure. The aerodynamic resistance, $r_a$, is determined by canopy architecture and wind velocity. Its calculation under non-stable conditions was discussed in detail by Hatfield et al. (1983). To adjust the estimated phytomass values for water stress, it will be assumed that if $E/E^* > 0.70$, then $C = 1.0$, otherwise $C$, is linearly proportional to the ratio of $E/E^*$ (Hodges and Kanemasu, 1977).

## Materials and Methods

Two experiments were conducted during the 1978–1979 and 1979–1980 growing seasons at the U.S. Water Conservation Laboratory in Phoenix, AZ (112°01′W longitude, 32°26′N latitude). The treatments included five planting dates (1–5) and three irrigation levels (A, B, and C) for Produra spring wheat (*Triticum durum* Desf.). Planting, emergence, irrigation dates, and total water applied to each treatment are presented in Table 1. Six plants were selected randomly from each treatment twice weekly for determining leaf area and total aboveground phytomass production.

Reflected radiation from the wheat canopies and a white barium sulfate reference panel were measured at nadir viewing position with a hand-held, 15° field of view Exotech Model 100-A radiometer.[1] This instrument has four wavelength bands 0.5–0.6, 0.6–0.7, 0.7–0.8, and 0.8–1.1 $\mu$m similar to the bands of the multispectral scanner (MSS) sensor on board LANDSAT satellites. Spectral reflectance measurements were conducted on clear days with solar zenith angle of about 57°. Canopy reflectance factors were calculated as a ratio of the canopy

[1] Trade names and company names are for the benefit of the reader and imply no endorsement or preferential treatment of the product listed by Kansas State University or the U.S. Department of Agriculture.

to a $BaSO_4$ reference panel radiances. Near-infrared ($\rho_n = 0.8$–$1.1\ \mu m$) and red ($\rho_r = 0.6$–$0.7\ \mu m$) canopy reflectance factors were used to compute a normalized difference (ND) as

$$ND = (\rho_n - \rho_r)/(\rho_n - \rho_r). \quad (5)$$

ND values were adjusted for early season effect of soil background, when soil is the dominant feature, and scattering of the near-infrared radiation by foliage elements to obtain an estimate for fraction of PAR absorbed ($\varepsilon_i$) by plants using the following empirical relation (Asrar et al., 1984b):

$$p = -0.185 + 1.20\text{ND}, \quad R^2 = 0.965. \quad (6)$$

Equation (6) was derived based on the data from the 1978–1979 experiment. These data then were excluded from further analysis to reduce the dependency of Eq. (6) on the data set. A value of 0.49 was used for $\varepsilon_s$. $\varepsilon_c$ was assumed to vary between vegetative and reproductive stages of growth, and its value was accordingly obtained from the work of Asrar et al. (1984a).

Plant canopy radiation temperatures were measured every nonrainy day between 1300 and 1400 h (MST) with a hand-held Telatemp Model AG-42 infrared thermometer with 4° FOV held at 30° from nadir. Eight measurements (four viewing east, four viewing west) were combined to obtain a mean value for each treatment.

Air temperature and vapor pressure, wind speed, and solar radiation were monitored at an elevation of 1.5 m above the soil surface. Net radiation was computed as

$$R_n = (1 - \alpha)S + \sigma(E_a T_a^4 - E_c T_c^4), \quad (7)$$

where $\alpha$ is surface albedo, $\sigma$ is Stefan–Boltzman constant, $E_a$ is the atmospheric emissivity, and $E_c$ is the surface emissivity. The surface albedo was computed as an average reflectance ($\bar{\rho}$), measured over the four wavelength bands of the Exotech radiometer (0.5–1.1 $\mu m$), which was related to the total albedo by

$$\alpha = 0.0172 + 1.064\bar{\rho}, \qquad R^2 = 0.992. \quad (8)$$

Equation (8) was developed from the same data and in a similar manner to the partial/total radiance calculations described by Jackson (1984). Atmospheric emissivity was computed (Brutsaert, 1975) as

$$E_a = 1.24(e_a/T_a)^{1/7}. \quad (9)$$

An average surface emissivity of 1.0 was assumed for wheat. Units of $T_c$ and $T_a$ in Eqs. (7) and (9) are degree $K$.

$r_c^*$ was obtained from published data of Russel (1980). Plant canopy height $z$ was computed using the following relation (J. T. Baker, personal communication):

$$z = B_0 \exp(B_1 CT), \quad (10)$$

where $T$ is the sum of thermal units $[(T_{max} + T_{min}/2)]$ above zero degree base temperature, $C$ is defined by Eq. (2), and $B_0 = 4.73$ and $B_1 = 0.0045$ are empirically derived coefficients for a medium height wheat canopy. Equation (1) was used to compute $M$ values from emergence until physiological maturity.

In the preceding development of Eqs. (2) and (4), soil heat flux was assumed to be negligible and, also, the equations of latent and sensible heat transfer were not adjusted for diabatic atmospheric conditions. These detailed refinement were not considered due to the simplifying assumptions that were made for estimating absorbed PAR from spectral reflectance measurements.

## Results and Discussion

The combination of five planting dates and three irrigation rates in Produra spring wheat resulted in canopies with diverse quantities of above-ground total phytomass. Estimates of total phytomass were made from spectral reflectance data with no adjustment [i.e., $C = 1$ in Eq. (1)] for water stress (method 1) and with phytomass values adjusted for water stress with canopy radiation temperature (method 2). Estimates made with these methods are compared with measured phytomass values in Figs. 1–4. The regression parameters for the linear relationship between the estimated phytomass values based on the two methods and the measured ones are presented in Tables 2 and 3.

Early planting in treatments A1, B1, and C1 resulted in a growing season of 180 days. The major difference between these treatments was the number of irrigations with B1 receiving ≅ 150 mm more water than A1 and C1 (Table 1). The increased applied water resulted in only 150 $g\,m^{-1}$ higher final phytomass in treatment B1 (Fig. 1). The lack of a more positive response to the increased level of water in B1 could be attributed to low mean daily insolation ($\bar{S} = 13.26$ $MJ\,m^{-2}d^{-1}$) due to shorter daylengths. The slopes of the linear regressions for estimated phytomass values based on

TABLE 2 Regression Parameters for the Linear Relation between Measured and Estimated Total Dry Phytomass[a]

| Treatment | Number of Measurements | Intercept | Slope[b] | $R^2$ | Standard Deviation |
|---|---|---|---|---|---|
| A1 | 33 | 69.30 | 0.996 | 0.944 | 119.52 |
| B1 | 32 | 59.48 | 0.900 | 0.967 | 95.10 |
| C1 | 32 | 74.78 | 0.638 | 0.898 | 134.77 |
| A2 | 39 | 130.90 | 0.830 | 0.960 | 157.04 |
| B2 | 35 | 109.17 | 0.944 | 0.962 | 128.79 |
| C2 | 35 | 135.85 | 0.913 | 0.971 | 113.13 |
| A3 | 30 | 60.72 | 0.860 | 0.956 | 122.66 |
| B3 | 30 | 88.54 | 0.704 | 0.944 | 150.58 |
| C3 | 26 | 46.36 | 0.936 | 0.983 | 67.91 |
| A4 | 17 | 71.39 | 1.042 | 0.984 | 97.53 |
| B4 | 18 | 105.86 | 0.955 | 0.962 | 166.38 |
| C4 | 18 | 31.87 | 1.020 | 0.976 | 121.40 |
| A5 | 16 | 99.33 | 1.557 | 0.967 | 123.19 |
| B5 | 18 | 150.39 | 1.328 | 0.981 | 107.76 |
| C5 | 18 | 47.31 | 2.007 | 0.991 | 69.26 |

[a] Estimated phytomass values were *not* adjusted for water stress.
[b] Predicted phytomass = A + B (measured phytomass).

**TABLE 3** Regression Parameters for the Linear Relation between Measured and Estimated Total Dry Phytomass[a]

| Treatment | Number of Measurements | Intercept | Slope[b] | $R^2$ | Standard Deviation |
|---|---|---|---|---|---|
| A1 | 33 | 100.00 | 0.773 | 0.945 | 100.00 |
| B1 | 32 | 67.73 | 0.758 | 0.956 | 92.81 |
| C1 | 32 | 69.16 | 0.633 | 0.899 | 130.50 |
| A2 | 39 | 131.93 | 0.827 | 0.956 | 149.69 |
| B2 | 35 | 72.15 | 0.857 | 0.985 | 83.53 |
| C2 | 35 | 128.27 | 0.820 | 0.980 | 103.62 |
| A3 | 30 | 30.30 | 0.900 | 0.959 | 113.13 |
| B3 | 30 | 21.33 | 0.777 | 0.924 | 140.99 |
| C3 | 26 | 27.84 | 0.873 | 0.989 | 51.03 |
| A4 | 17 | 68.22 | 1.023 | 0.985 | 90.04 |
| B4 | 18 | 99.22 | 0.959 | 0.961 | 148.18 |
| C4 | 18 | 28.04 | 1.072 | 0.977 | 112.78 |
| A5 | 16 | 92.81 | 1.485 | 0.970 | 110.38 |
| B5 | 18 | 93.85 | 1.309 | 0.985 | 95.67 |
| C5 | 16 | 46.19 | 1.899 | 0.994 | 52.76 |

[a] Estimated phytomass values were adjusted for water stress based on canopy radiation temperature measurements.
[b] Predicted phytomass = A + B (measured phytomass).

method 1 were closer to unity, but the standard deviations were smaller for method 2. The coefficients of determination ($R^2$) indicated a good agreement between measured and simulated phytomass values for both methods for the early planting.

Figure 2 shows the relationship between the estimated and measured phytomass values for treatment B2 of the second planting date. This treatment received three irrigations prior to day 325. The total water applied to treatment B2 was 215 mm less than treatment B1 (Table 1). Also, a delay in planting (24 days compared with the first date) resulted in a shorter (10 days) growing season. In spite of a reduction in applied water for the second planting treatment and a shorter growing season, the total phytomass produced was significantly ($p = 0.05$) greater than that of the first planting treatment. This increase in phytomass production resulted from the delay in planting that caused the major period of the growing season to coincide with periods of higher mean daily insolation ($\bar{S} = 14.65\ \mathrm{MJ\,m^{-2}d^{-1}}$) for the second planting date. A visual comparison between the estimated and measured phytomass values (Fig. 2) demonstrated a need for adjusting the phytomass values during a water limiting period (after day 325). This is supported by the smaller standard deviations and higher $R^2$ values that indicate a better agreement between the measured and estimated phytomass values based on method 2 (Tables 2 and 3).

The estimated and measured phytomass values for the fourth planting date, treatment B4, are presented in Fig. 3. Planting on the fourth date was delayed 81 days (compared with the first date), which resulted in a growing season of 135

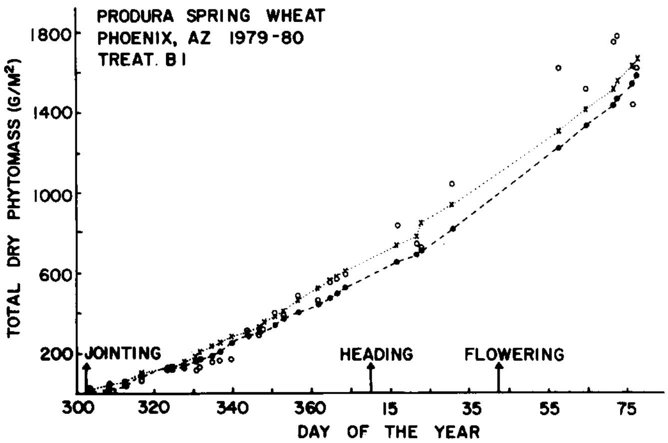


FIGURE 1. Estimated and measured total dry phytomass values for Treatment B1: first planting date and five irrigations. In method 2 (•---•), phytomass estimates were corrected for water stress: (O) measured; (x) estimated 1; (●) estimated 2.

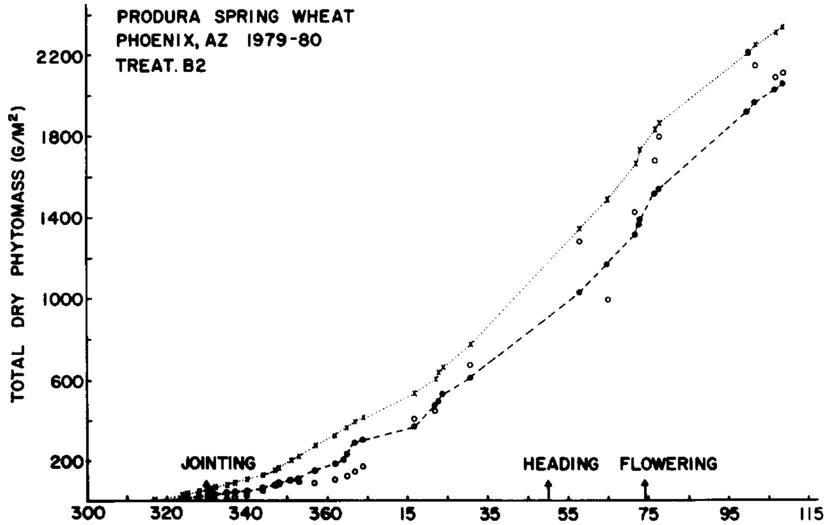


FIGURE 2. Estimated and measured total dry phytomass values for Treatment B2: second planting and three irrigations. In method 2 (•----•), phytomass estimates were corrected for water stress: (O) measured; (x) estimated 1; (●) estimated 2.

days. The total amount of water applied to treatments A4, B4, and C4 was 276, 239, and 165 mm less than treatments A1, B1, and C1, respectively. The total above-ground phytomass produced by A4, B4, and C4 was significantly ($\rho = 0.05$) greater than that produced by A1, B1, and C1, in spite of a shorter growth period and reduced applied water. The delay in planting caused the major period of the growing season to coincide with a period of high mean daily insolation ($\bar{S} = 16.99$ $MJ m^{-2} d^{-1}$) for A4, B4, and C4. When energy was not a limiting factor, uniform application of 200 mm additional water throughout the season in treatment B4

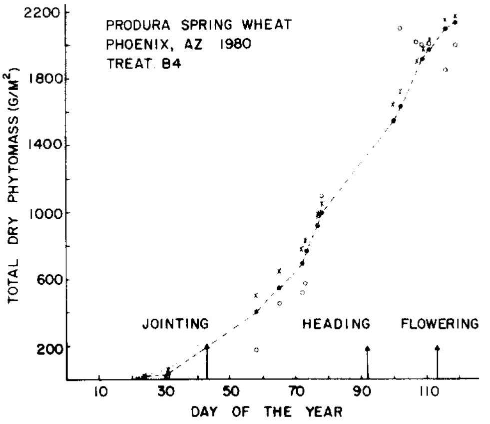


FIGURE 3. Estimated and measured total dry phytomass values for Treatment B4: fourth planting and three irrigations. In method 2 (·----·), phytomass estimates were corrrected for water stress: (○) measured; (x) estimated 1; (●) estimated 2.

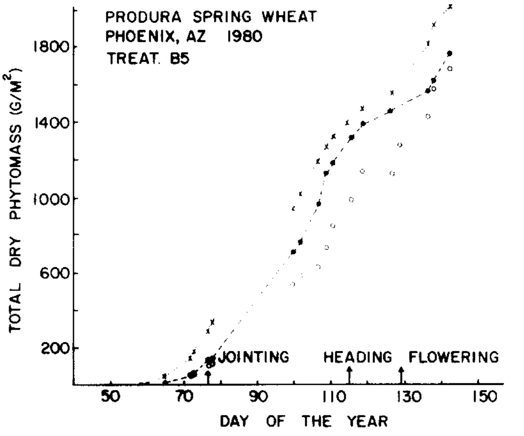


FIGURE 4. Estimated and measured total dry phytomass values for Treatment B5: fifth planting date and five irrigations. In method 2 (·----·), phytomass estimates were corrected for water stress: (○) measured; (x) estimated 1; (●) estimated 2.

(Table 1) resulted in a significantly ($p = 0.05$) higher production of above-ground phytomass than in treatment A4. Good agreement was obtained between the measured and estimated phytomass values according to both methods, since water was not a limiting factor for this treatment (Fig. 3). Correlation of estimated phytomass values with measured ones showed lower standard deviations for method 2 than for method 1 (Tables 2 and 3).

The relationship between the estimated and measured phytomass values for treatment B5 of the last planting date is demonstrated in Fig. 4. In A5, B5, and C5 planting was delayed 126 days (compared with the first planting) which resulted in a total growth period of 100 days. Treatments A5, B5, and C5 received 196, 78, and 119 mm less water than A1, B1, and C1, respectively. The estimated phytomass values based on both methods overestimate the measured ones. This is depicted in the slopes of the linear regression lines (Tables 2 and 3), which were significantly ($p = 0.05$) greater than 1 for both methods. The overall poor agreement between the estimated and the measured values for treatments A5, B5, and C5 was due to a very late planting into a dry soil during a warm period with increasing daylength. An additional 277 mm water applied uniformly through the season in treatment B5 (compared with A5), resulted in a significantly ($p = 0.05$) higher phytomass production, which demonstrated the need for additional water during a warm period with adequate energy ($\bar{S} = 21.76$ $\mathrm{MJ\,m^{-2}d^{-1}}$). The close agreement between measured and estimated phytomass values based on method 2 suggests the need for an index that allows for a proper adjustment of the estimated phytomass values under stressful conditions. The discrepency between the estimated and measured phytomass values for this treatment could be attributed to incomplete canopy cover due to delayed plant development. This resulted in an overestimate of PAR absorbed by plants, due to the influence of soil background on canopy reflectance and, hence, an overestimate of produced phytomass.

Also, under partial canopy cover the soil heat flux is a significant component that should be considered in the energy balance of the canopy. Soil heat flux was assumed negligible in deriving Eqs. (2) and (4). Therefore, the incomplete plant canopy caused incorrect partitioning of solar energy for dry phytomass production, as well as in the energy balance of the canopy. The overall standard deviation of estimated to measured phytomass values for all treatments combined for methods 1 and 2 was 171 and 150 $\mathrm{g\,m^{-2}}$, respectively.

The proposed methods adequately depicted the major changes, due to management practices, on spectral properties of the plant canopies and, hence, the changes in above-ground total phytomass production. Using a paired sign-test, 15 out of 15 times the standard deviations of the estimated phytomass values based on method 2 were smaller than those of method 1. This difference was significant at any probability level $> 0.00003$. This supports the usefulness of canopy radiation temperature as a stress indicator.

## Summary and Conclusions

A combination of measured reflected visible and near-infrared and emitted thermal radiation from several planting dates and irrigation rates of spring wheat canopies were used to estimate total above-ground phytomass production.

Early planting resulted in a longer growth period; however, a major period of the growth coincided with shorter daylengths and low isolation. During this energy limiting period, application of additional water did not result in a significant increase in phytomass production. As planting was delayed, the growth period coincided with longer days and higher insolation. Decreased water and its nonuniform application during this period suppressed the growth and resulted in a significant decrease in above-ground phytomass production. The changes in plant-canopy condition and development, due to management practices and climate condition, were depicted in their spectral characteristics.

The estimated phytomass values, based on a physical and physiological model and multispectral reflectance measurements, were strongly correlated with the measured ones. The standard error of estimates was significantly improved when canopy radiation temperature was used as a stress indicator to adjust the estimated phytomass values. The estimated phytomass values overestimate the measured ones in sparse canopies due to improper partitioning of solar energy in the radiation and energy balances of the canopy.

The proposed method requires multitemporal measurements of canopy reflectance and radiation temperature, and meteorological data. The frequency of measurements depends on the condition and stage of development of the plant canopy.

## References

Aase, J. K., and Siddoway, F. H. (1981), Assessing winter wheat dry matter production via spectral reflectance measurements, *Remote Sens. Environ.* 11:267–277.

Asrar, G., Hipps, L. E., and Kanemasu, E. T. (1984a), Assessing solar energy and water use efficiencies in winter wheat: A case study, *Agric. Forest Meteorol.* 31:47–58.

Asrar, G., Fuchs, M., Kanemasu, E. T., and Hatfield, J. L. (1984b), Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat, *Agron. J.* 76:300–306.

Asrar, G., Kanemasu, E. T., and Yoshida, M. (1985c), Estimates of leaf area index from spectral reflectance of wheat under different cultural practices and solar angle, *Remote Sens. Environ.*, forthcoming.

Brutsaert, W. (1975), On a derivable formula for long-wave radiation from clear skies, *Water Resour. Res.* 11:742–744.

Daughtry, C. S. T., Gallo, K. P., and Bauer, M. E. (1983), Spectral estimates of solar radiation intercepted by corn canopies, *Agron. J.* 75:527–531.

Hatfield, J. L., Perrier, A., and Jackson, R. D. (1983), Estimation of evapotranspiration at one time-of-day using remotely sensed surface temperature, *Agric. Water Manag.* 7:341–350.

Hatfield, J. L., Asrar, G., and Kanemasu, E. T. (1984a), Intercepted photosynthetically active estimated by spectral reflectance, *Remote Sens. Environ.* 14:65–75.

Hatfield, J. L., Kanemasu, E. T., Asrar, G., Jackson, R. D., Pinter, P. J., Jr., Reginato, R. J., and Idso, S. B. (1984b), Leaf area estimates from spectral reflectance measurements over various planting dates of wheat, *Int. J. Remote Sens.*, forthcoming.

Hipps, L. E., Asrar, G., and Kanemasu, E. T. (1983), Assessing the interception of photosynthetically active radiation in winter wheat, *Agric. Meteorol.* 28:253–259.

Hodges, T., and Kanemasu, E. T. (1977), Modeling daily dry matter production of winter wheat, *Agron. J.* 69:974–978.

Idso, S. B., Jackson, R. D., and Reginato, R. J. (1977), Remote sensing of crop yields, *Science* 196:19–25.

Jackson, R. D. (1982), Canopy temperature and crop water stress, *Advances in Irrigation* (D. Hillel, Ed.), Academic, New York, pp. 43–85.

Jackson, R. D. (1984), Total reflected solar radiation calculated from multi-band sensor data, *Agric. Forest Meteorol.*, forthcoming.

Jackson, R. D., Reginato, R. J., and Idso, S. B. (1977), Wheat canopy temperature: A practical tool for evaluating water requirements, *Water Resour. Res.* 13:651–656.

Monteith, J. L. (1972), Solar radiation and productivity in tropical ecosystems, *J. Appl. Ecol.* 9:747–766.

Monteith, J. L. (1977), Climate and the efficiency of crop production in Britain, *Phil. Trans. Roy. Soc. London, Ser. B* 281:277–294.

Monteith, J. L., and Szeicz, G. (1962), Radiative temperature in the heat balance of natural surfaces, *Q. J. Roy. Meteorol. Soc.* 88:496–507.

Park, J. K., and Deering, D. W. (1982), Simple radiative transfer model for relationships between canopy biomass and reflectance, *Appl. Opt.* 21:303–309.

Russel, G. (1980), Crop evaporation, surface resistance and soil water status, *Agric. Meteorol.* 21:213–226.

Szeicz, G. (1974), Solar radiation for plant growth, *J. Appl. Ecol.* 11:617–636.

Tucker, C. J., Holben, B. N., Elgin, J. H., and McMurterey, J. E., III, (1981), Remote sensing of total dry-matter accumulation in winter wheat, *Remote Sens. Environ.* 11:171–189.

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